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Super-Resolution Algorithms for Ultrasonic Nondestructive Evaluation Imaging

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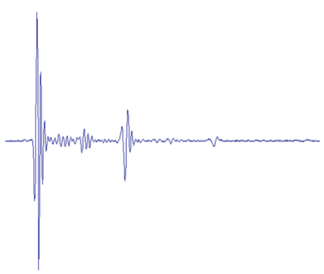
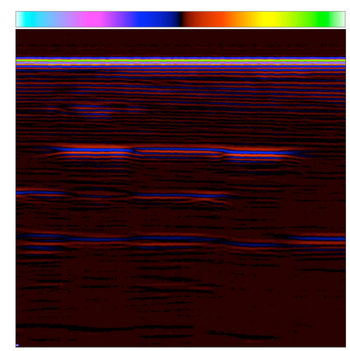
Super-Resolution Algorithms for Ultrasonic Nondestructive Evaluation Imaging

Grace A. Clark

Jessie A. Jackson



November 29, 2006



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Agenda

- Problem Definition:
  - Ultrasonic NDE measurements
  - The spatial resolution problem
- *Impulse Response Estimation* for Enhancing Spatial Resolution
  - Mitigate “ringing” due to the transducer and propagation paths
- *Bandlimited Spectrum Extrapolation* for Super-Resolution
- Examples of Processing Results

Ultrasonic Pulse-Echo Signals *(A-Scans)* Are *Distorted* By the *Transducer* and the *Propagation Paths ("Ringing")*

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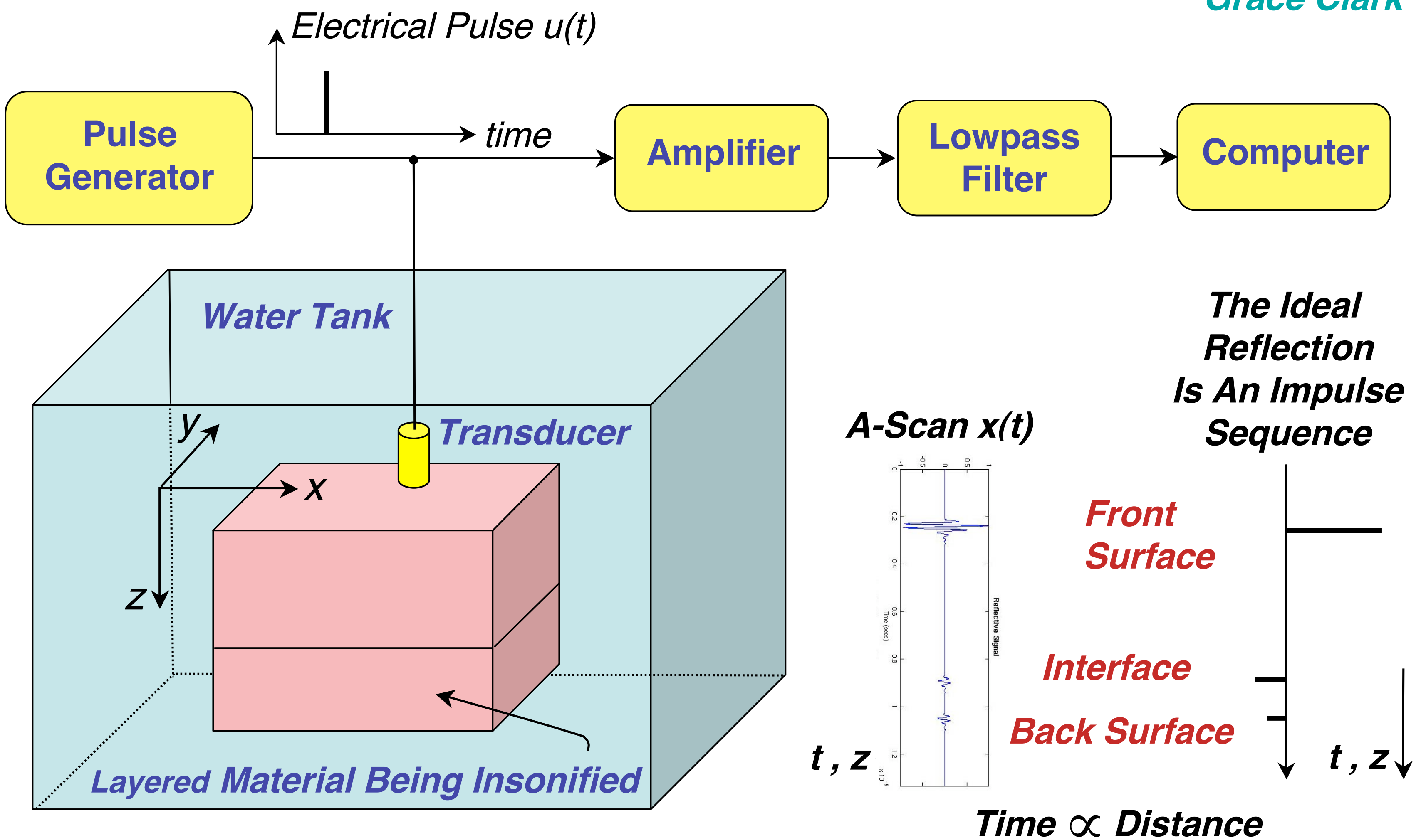
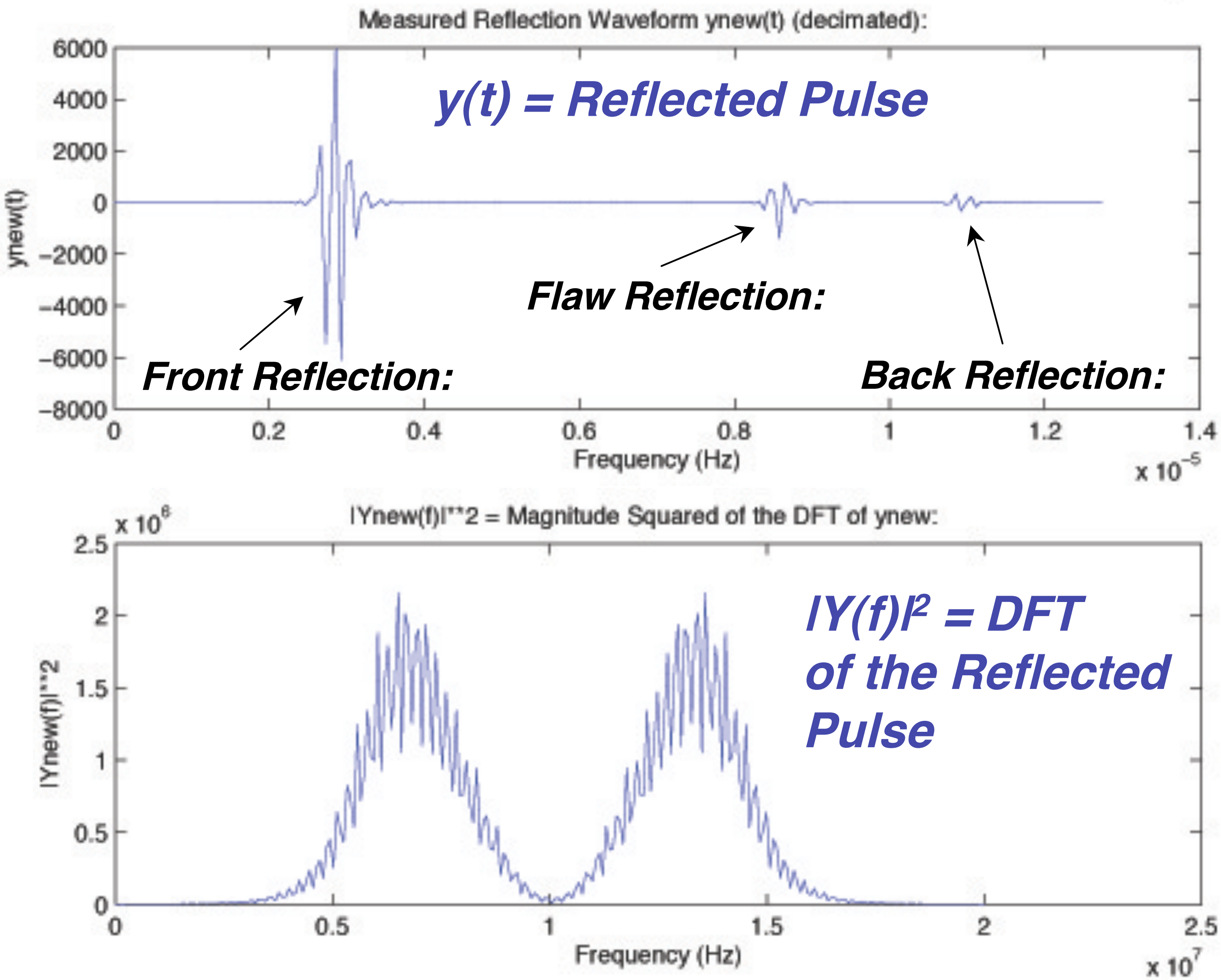


Ultrasonic Pulses Are *Bandlimited* by the Transducer ==> The Pulses *"Ring"*, *Reducing Spatial Resolution*



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We Define Ultrasonic *A-, B-, and C-Scans* Used in Nondestructive Evaluation (NDE) Studies:

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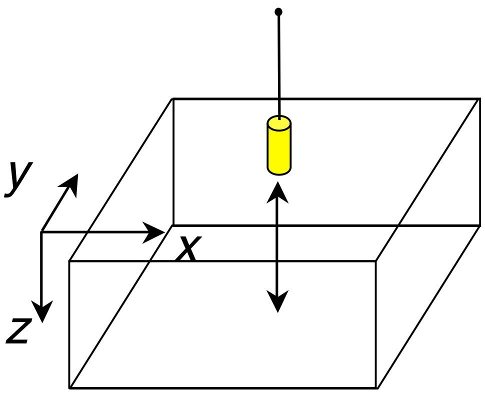
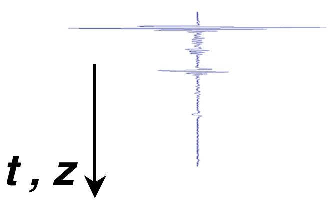
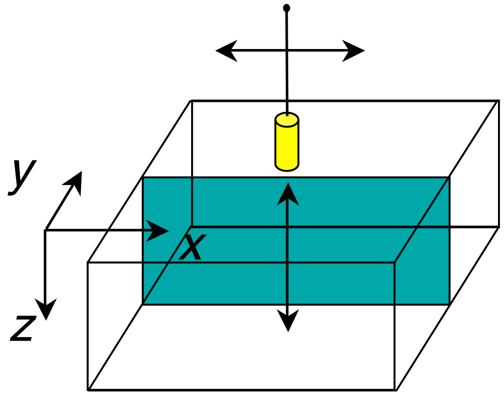


A-Scan x(t)

(A Single Waveform)

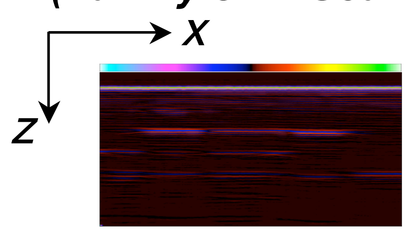


Time ∝ Distance



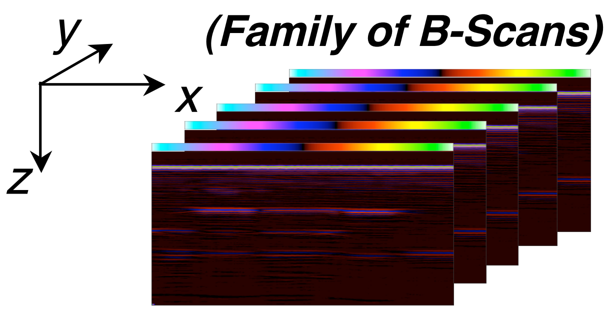
B-Scan

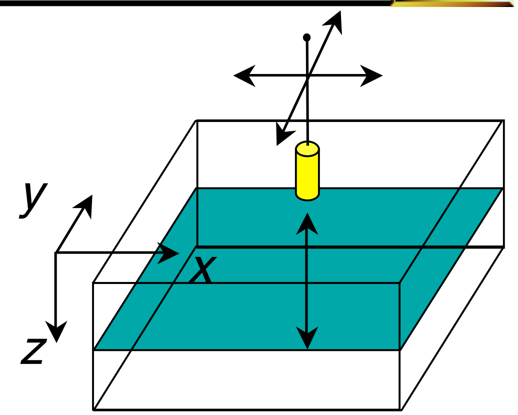
(Family of A-Scans)



3D Volume

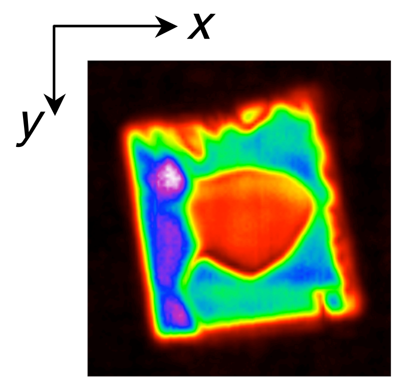
(Family of B-Scans)





C-Scan

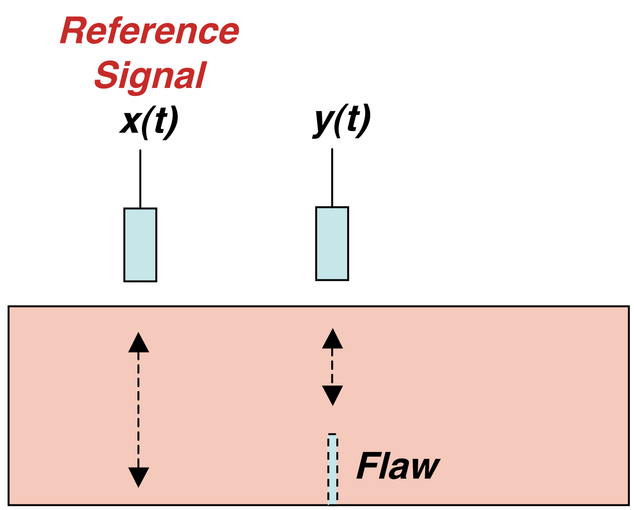
(Horizontal Slice At Depth z: Use A Time Gate)



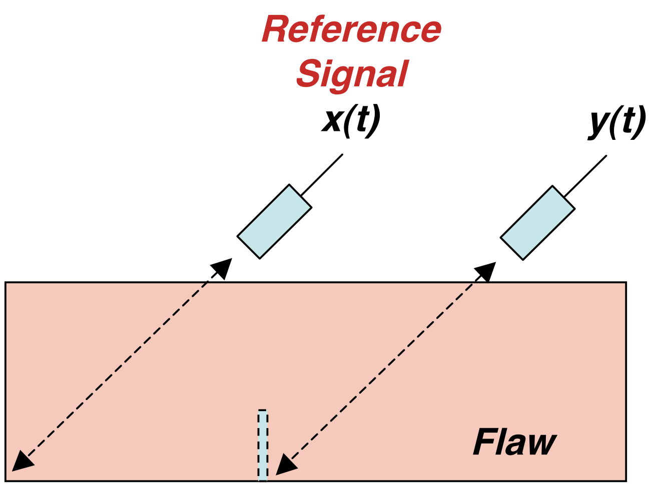
The Reference Scatterer is Chosen to Provide the Transducer / Path Response in the Absence of a Flaw

Desired properties of the reference scatterer:

- ***Reflects back most of the energy***
- ***Resembles some feature associated with the flaw environment***



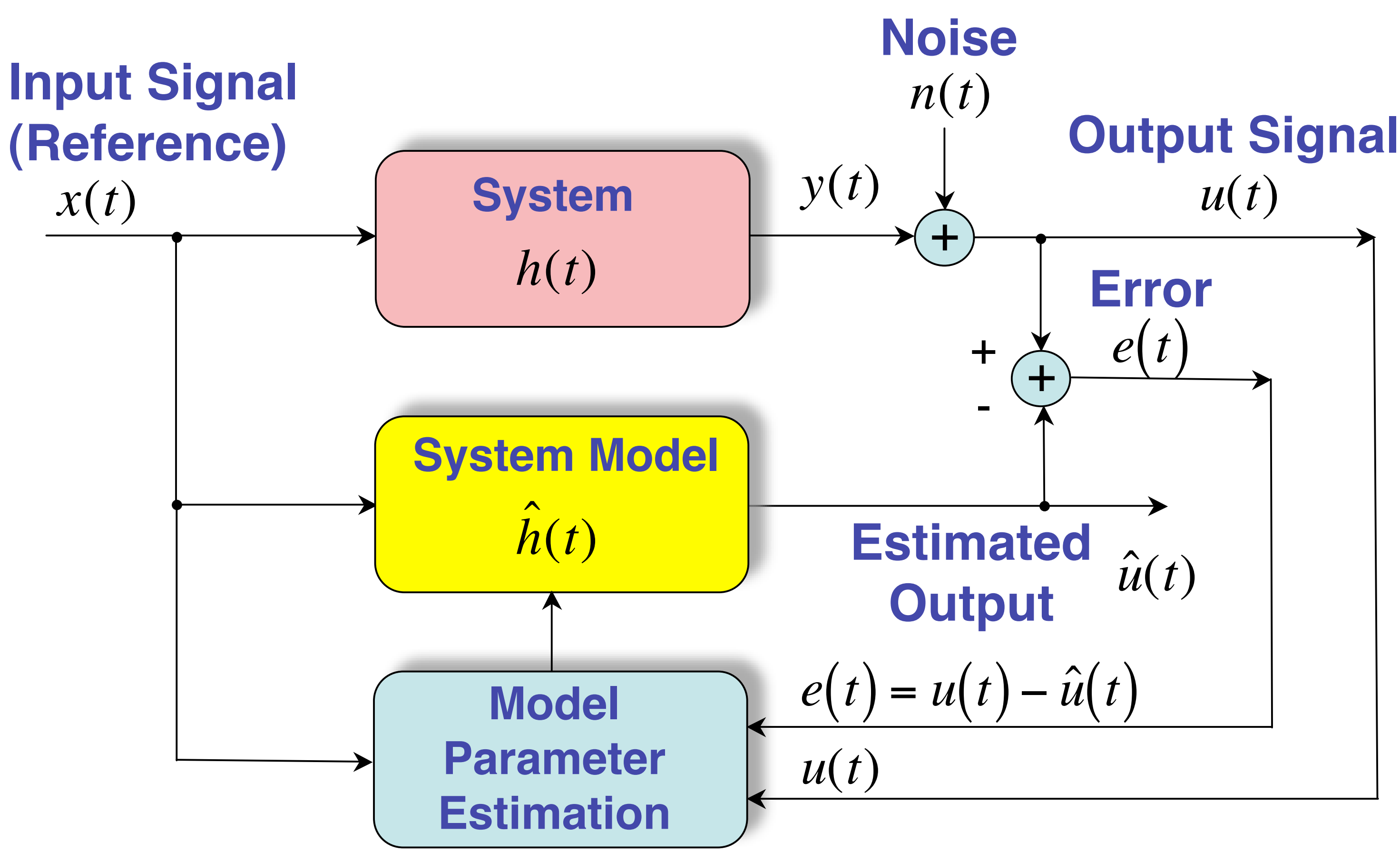
Front or Back Surface Reference



Corner Reflector Reference

System Identification: Estimate the Impulse Response $\hat{h}(t)$

Given: $x(t)$ **and** $u(t)$ **Estimate:** $\hat{h}(t)$



The Inverse Problem Is Very Difficult
We Must Regularize the Problem

- Ill-Posed
  (Infinite Number
  of possible
  solutions)
- Bandlimited
  Transducer
  Spectral
  Response
- Ill-Conditioned -
  Numerical Errors
  Due to Spectral
  Zeros

The *System Model* and *Processing Algorithms* Are Summarized in Block Diagrams

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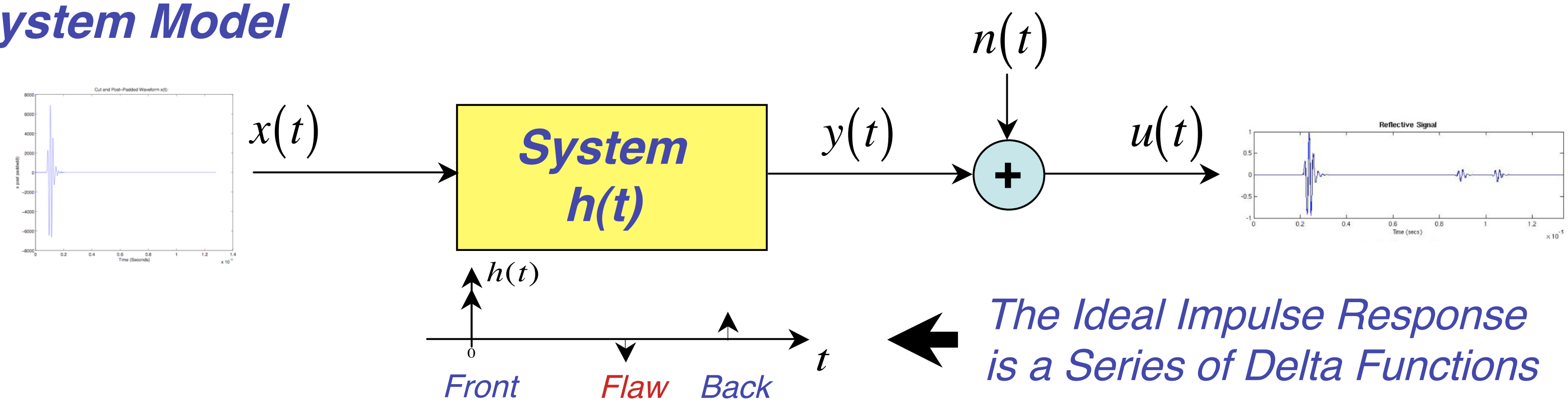
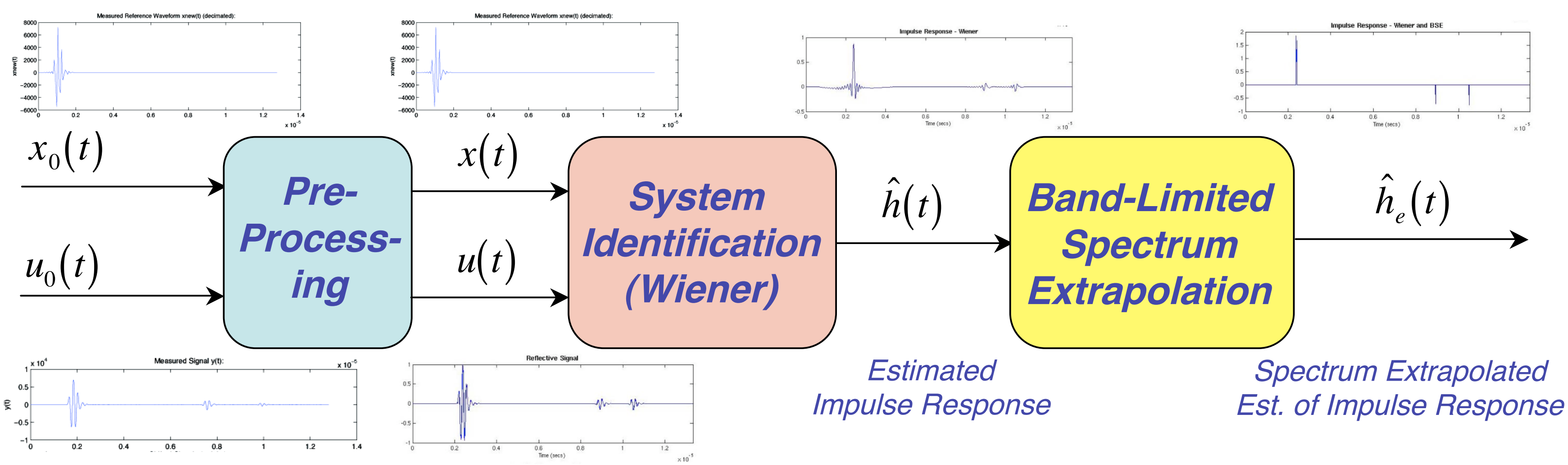
System Model

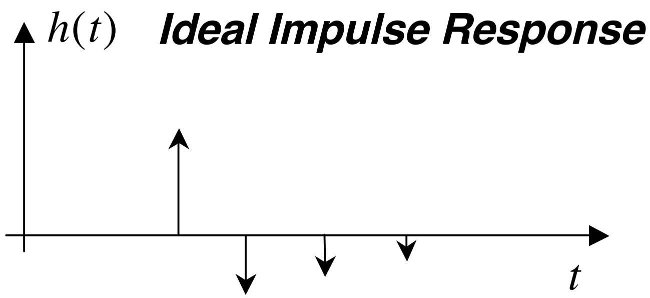


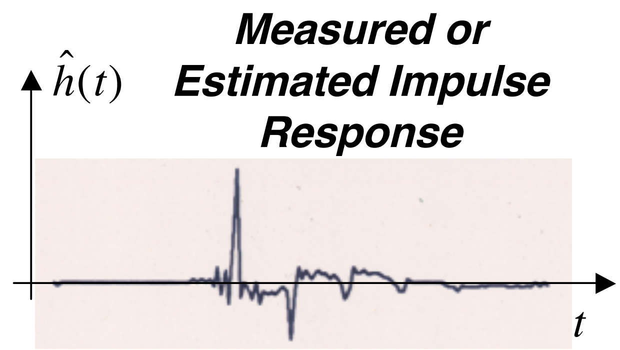
Processing Algorithms

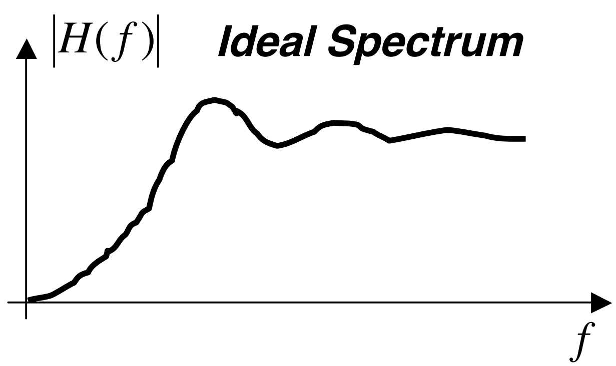


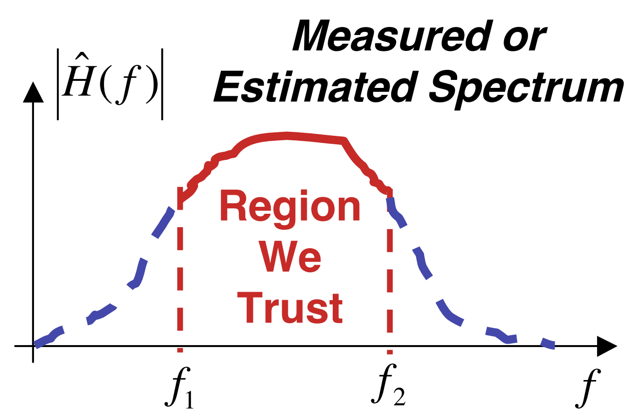
We Use *Bandlimited Spectrum Extrapolation* To Improve *Spatial Resolution*

Ideal	Measured or Estimated









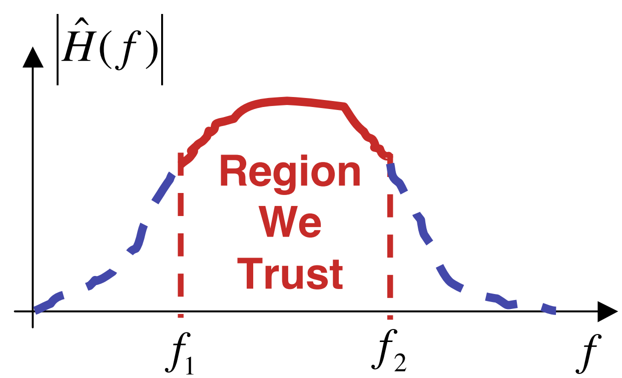
$h(t)$

Complex Variable Theory Gives Us a Solid Theoretical Basis for Spectrum Extrapolation

- Our temporal signals have *bounded support*:
  - They are transient (finite length) signals in the time domain

- The Fourier Transform of a signal with bounded support is *ANALYTIC* (continuous, all derivatives exist).

- If any analytic function in the complex plane is known exactly in an arbitrarily small (but finite) region of that plane, then the *entire function* can be found *(uniquely)* by *ANALYTIC CONTINUATION*.



Analytic Continuation Algorithms are Hypersensitive to Noise - *Must Regularize*

- Prior knowledge can be used as constraints to regularize the problem
- Iterative algorithms *(method of successive approximations)* are *slow*, not *unique*, but *can incorporate constraints*.
- Non-iterative algorithms are faster, but can't usually incorporate constraints.
- Often, it is not necessary to determine the inverse of the distortion operator
  - Good for nonlinear or time-varying operators

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We Use an Iterative Algorithm for *Regularized* Analytic Continuation

- Estimate the impulse response at the next iteration as a function F of the impulse response at the last iteration:

$$h_{k+1}(t) = F h_k(\mathrm{t}), \qquad \text{for } k = 0, 1, 2, \cdots$$

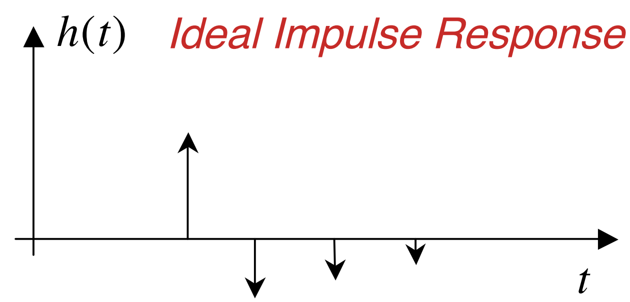
- Iterate between the time and frequency domains *(Method of Alternating Orthogonal Projections)*

- Convergence is proved using contraction mapping theorems from functional analysis

- Use an *"adaptive algorithm"* that assumes the impulse response to be a sequence of impulses - *constrain the time domain signal to be an impulse train:*

$$h(t) = \sum_i c_i \delta(t - t_i)$$

$$u(t) = \sum_i c_i x(t - t_i) + n(t)$$

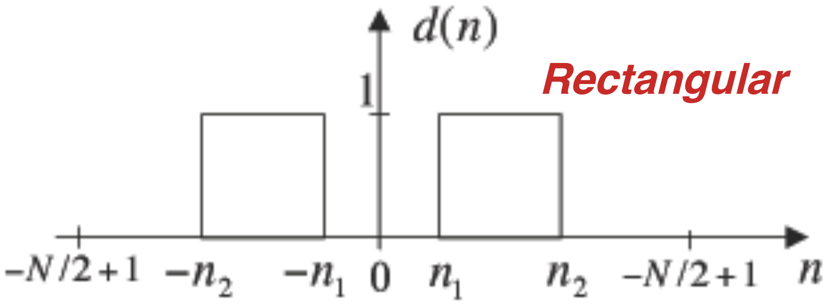


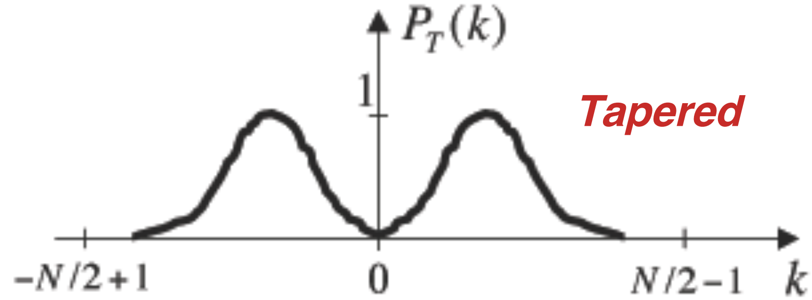
We Constrain the Temporal and Spectral *Support* Using *Projection Operators*

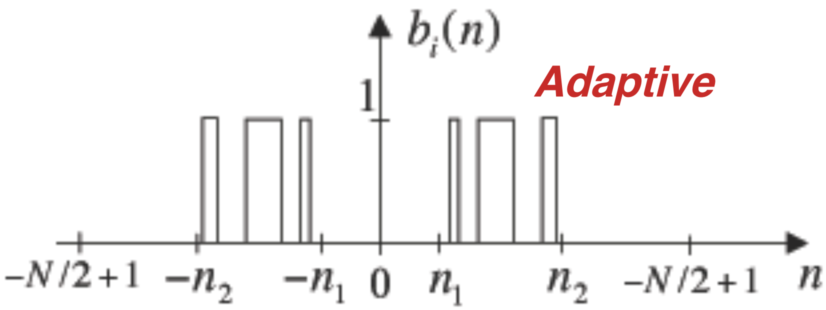
Temporal Projection Operators

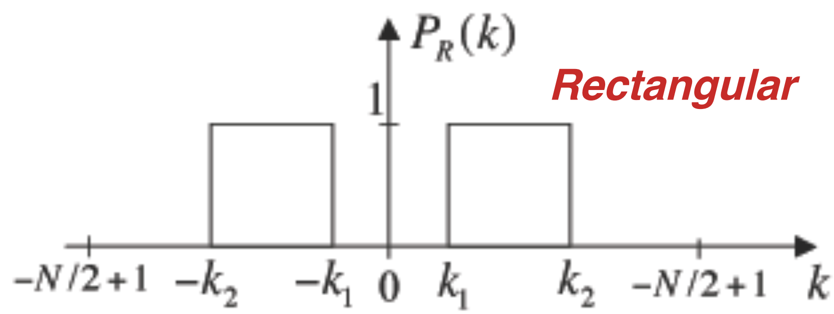
Spectral Projection Operators

$$P_T(k) = \text{Envelope}\left\{ \frac{|X(k)|}{\max|X(k)|} \right\}$$

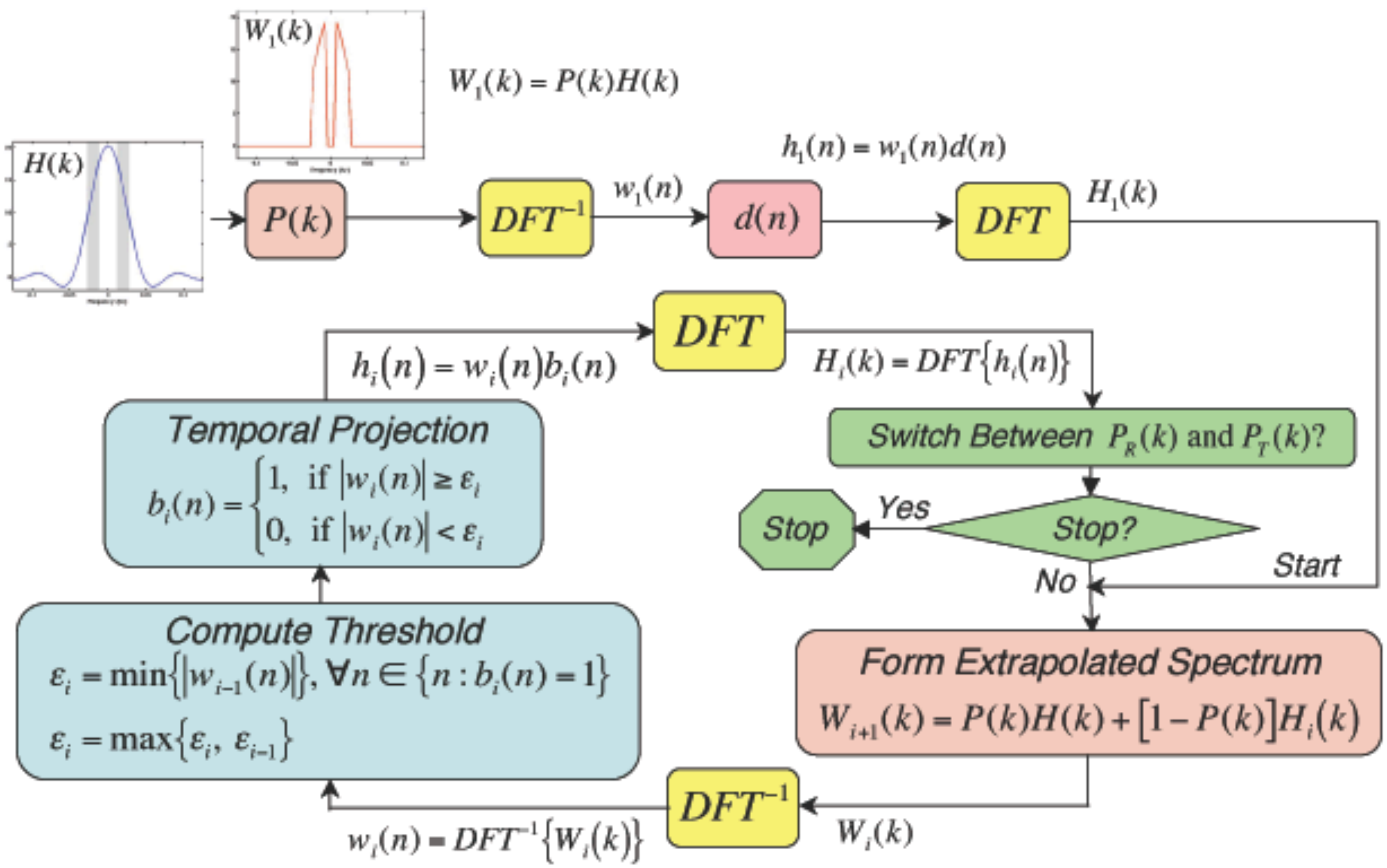




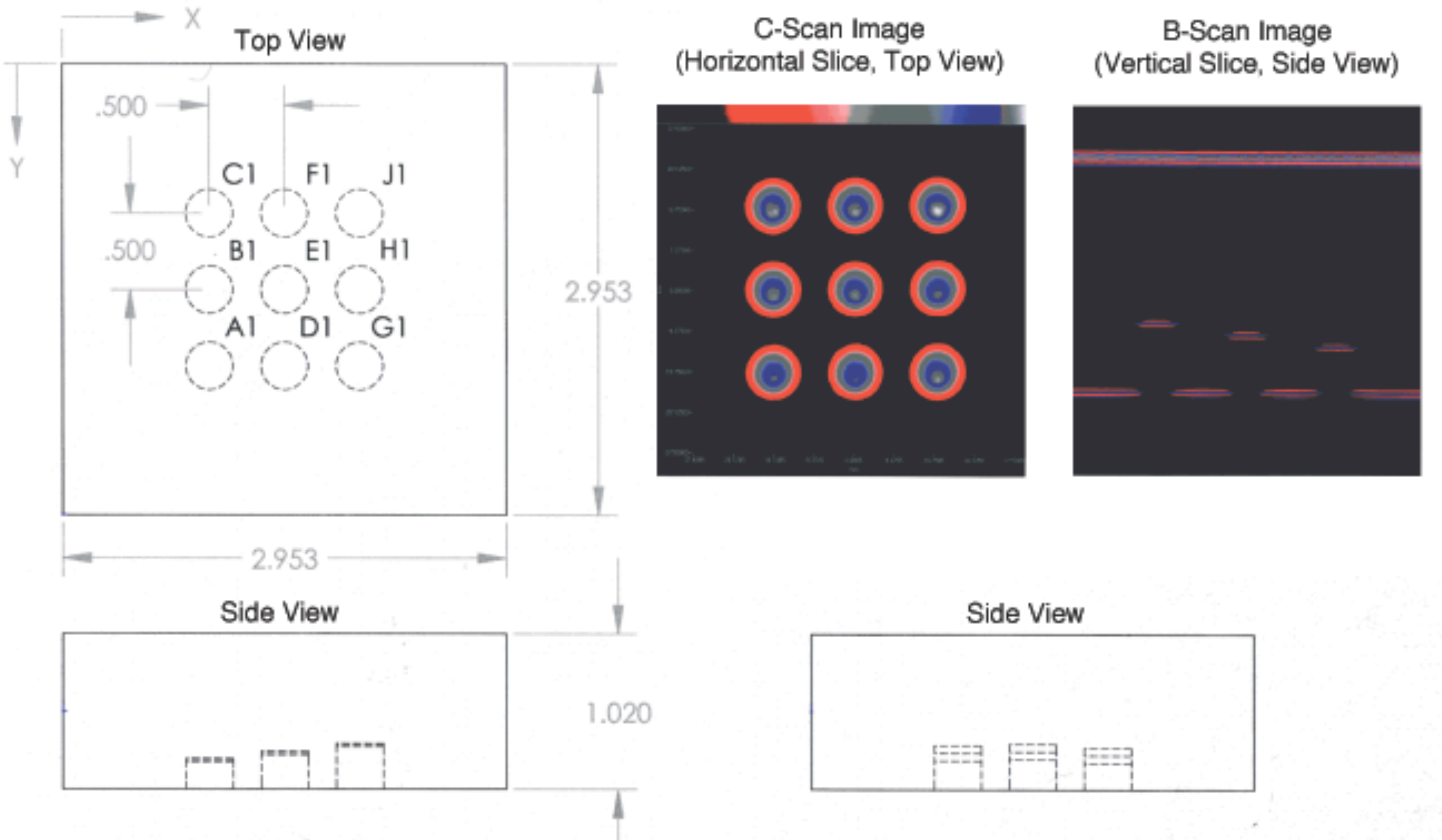




ith Iteration of the Spectrum Extrapolation Algorithm: *Alternating Orthogonal Projections, w/Adaptive Algorithm*

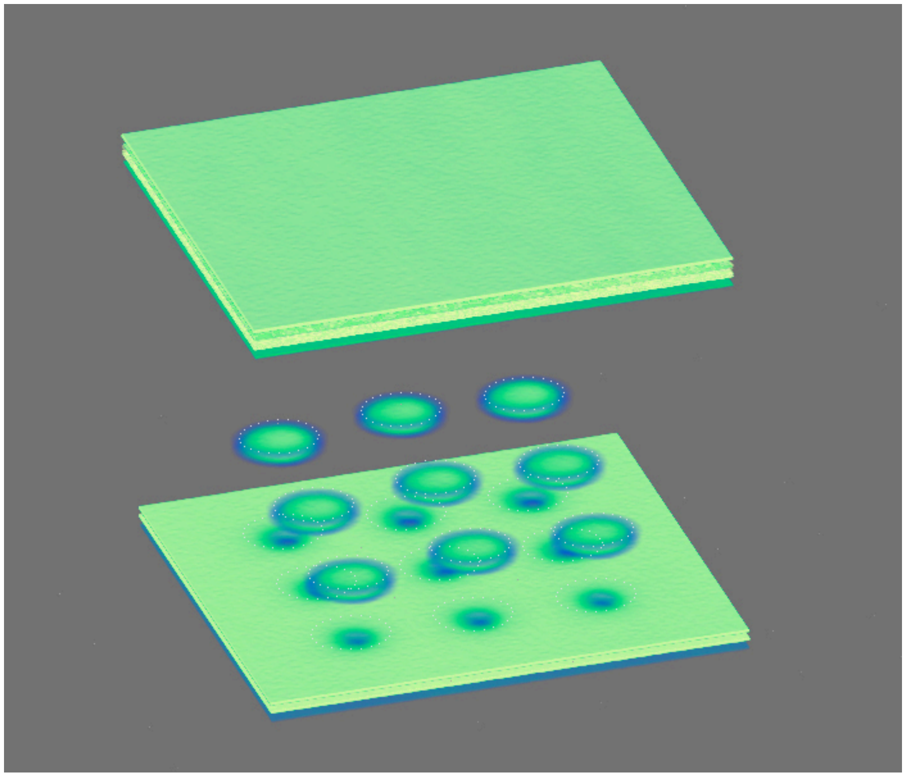


We Constructed a “Phantom” Part - *Aluminum Block* Containing *Flat-Bottom Holes*

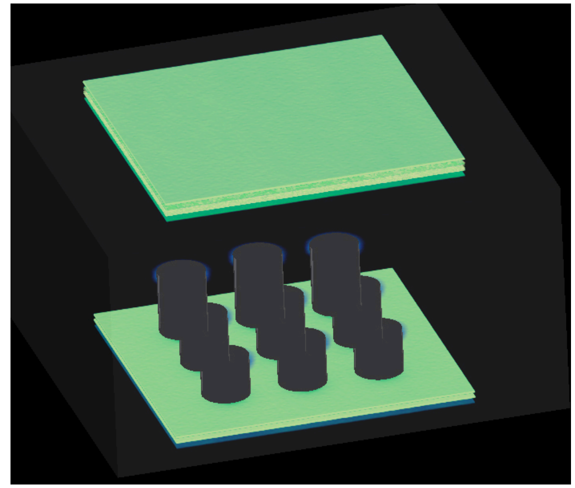


We Can Combine CAD Models With 3-D Data To Clarify Ultrasonic Evaluation Results

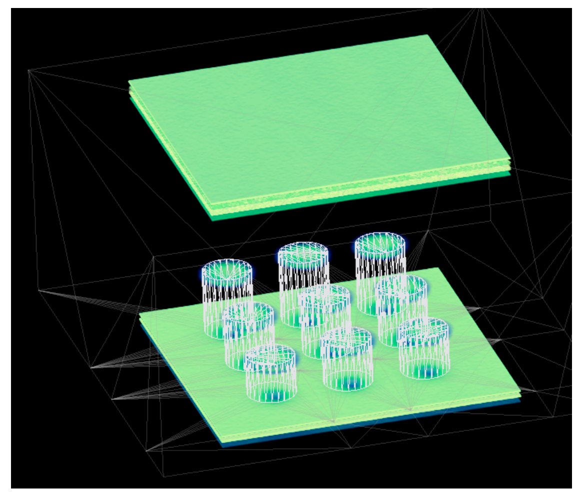
3-D Ultrasonic Data Set



3-D data and CAD Model-*Solid*



3-D data and CAD Model-*Lines*



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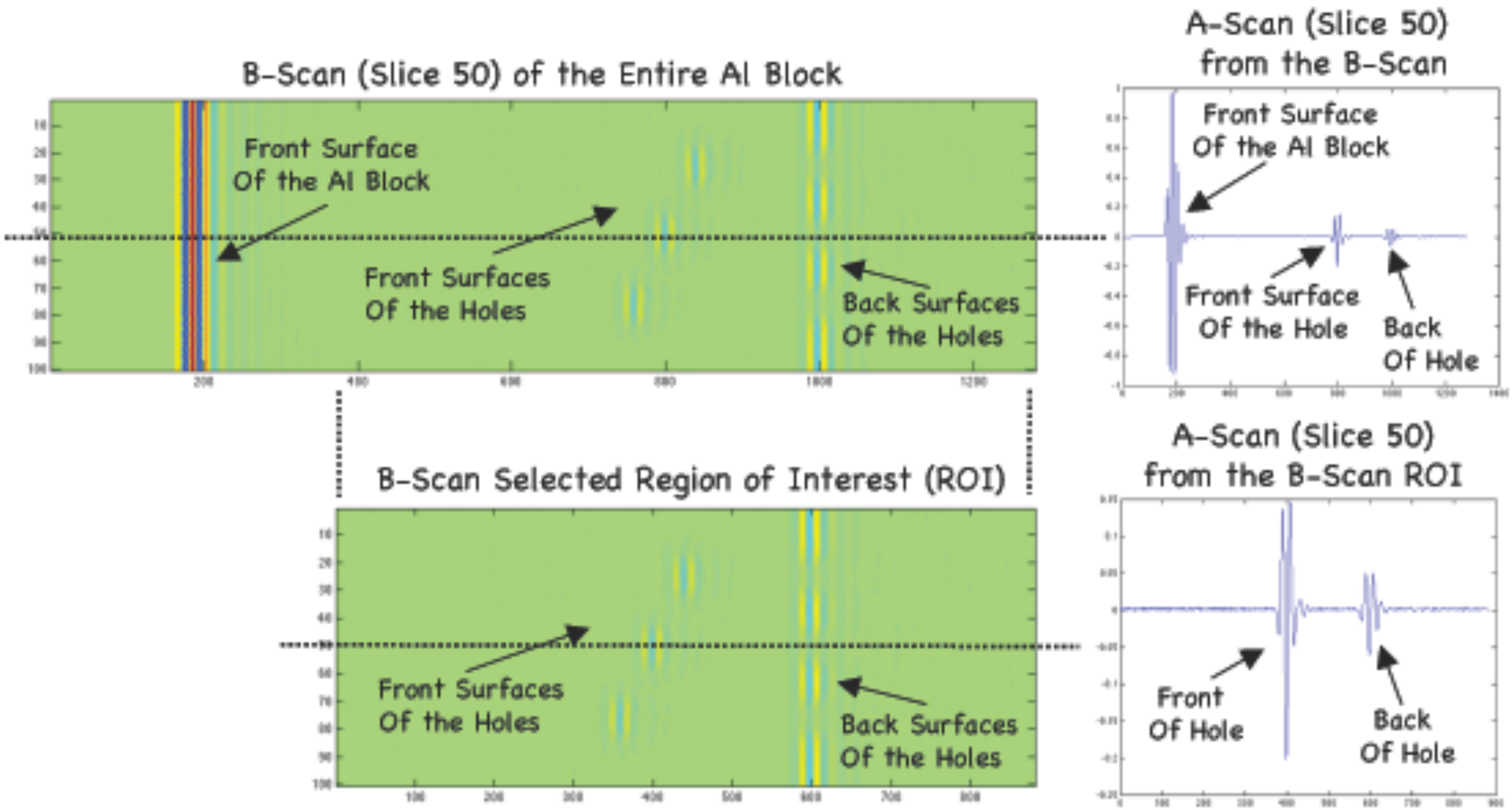
A-scan and B-scan Data Show that Material Interface Reflections Are Blurred Because of Transducer Ringing



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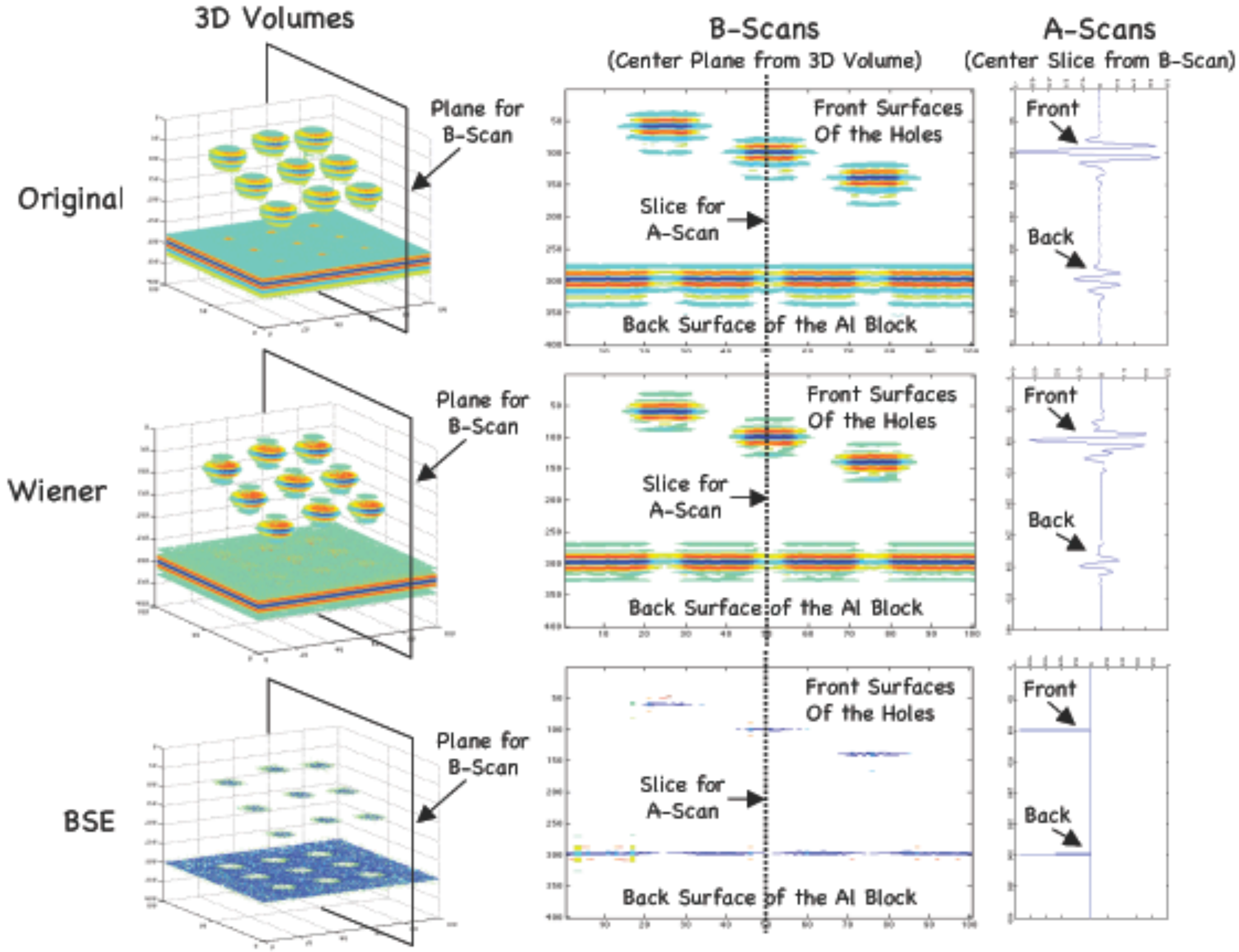
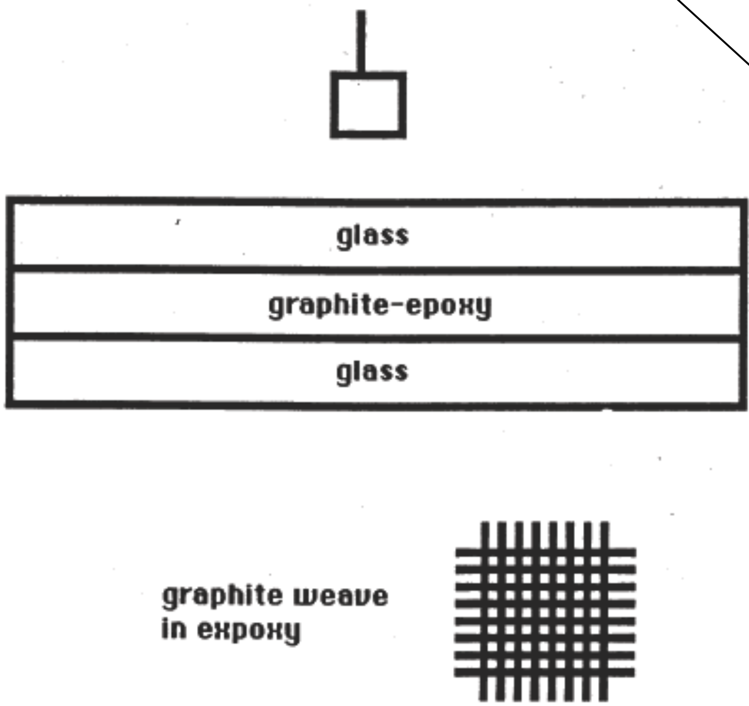
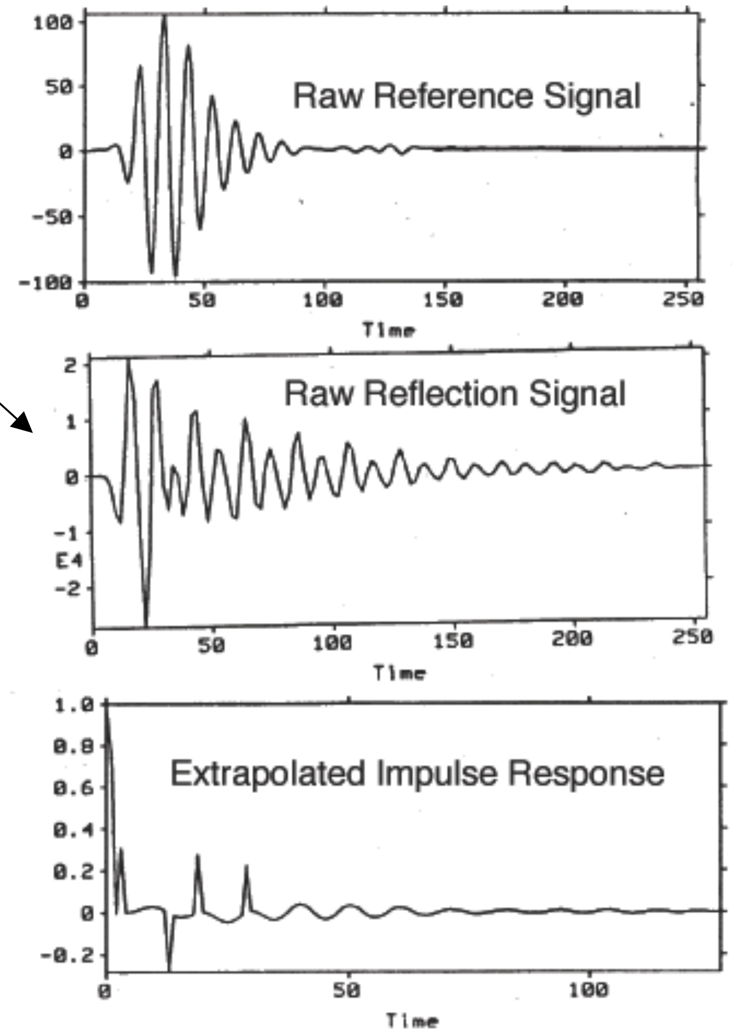
System Identification and Spectrum Extrapolation Results Are *Summarized* for the *Flat-Bottom Hole Phantom* Signals



Graphite Fiber Composite Material: *Thickness Measurements from Superimposed Layer Reflections*

The layer thicknesses are much smaller than the transducer ring-down time





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Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths

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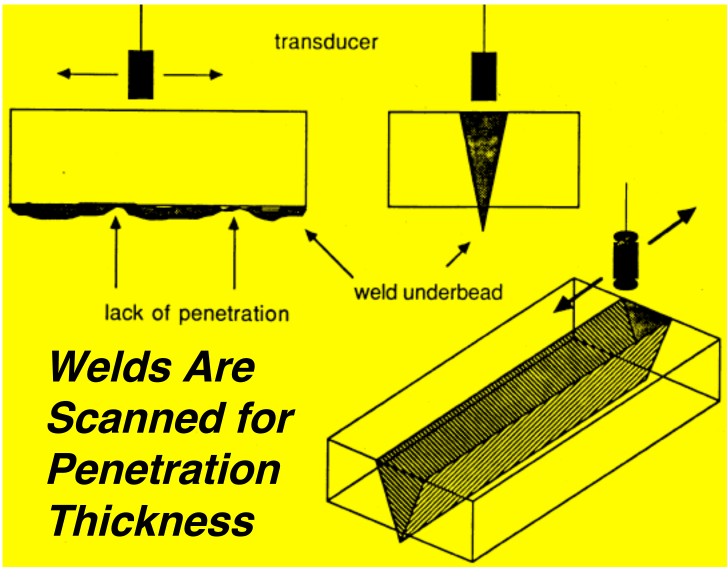

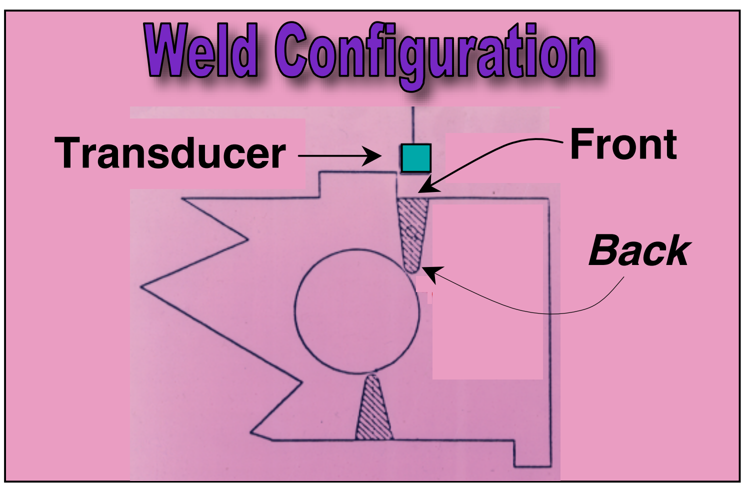

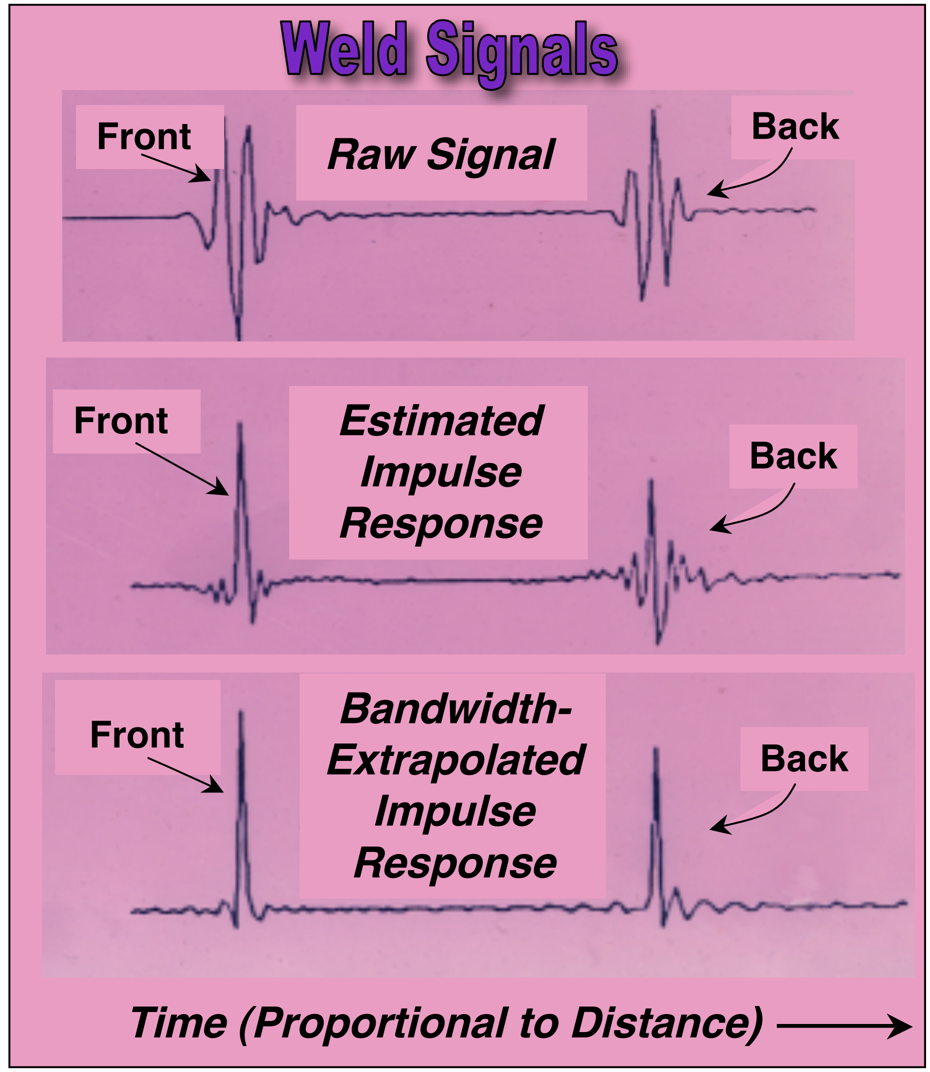

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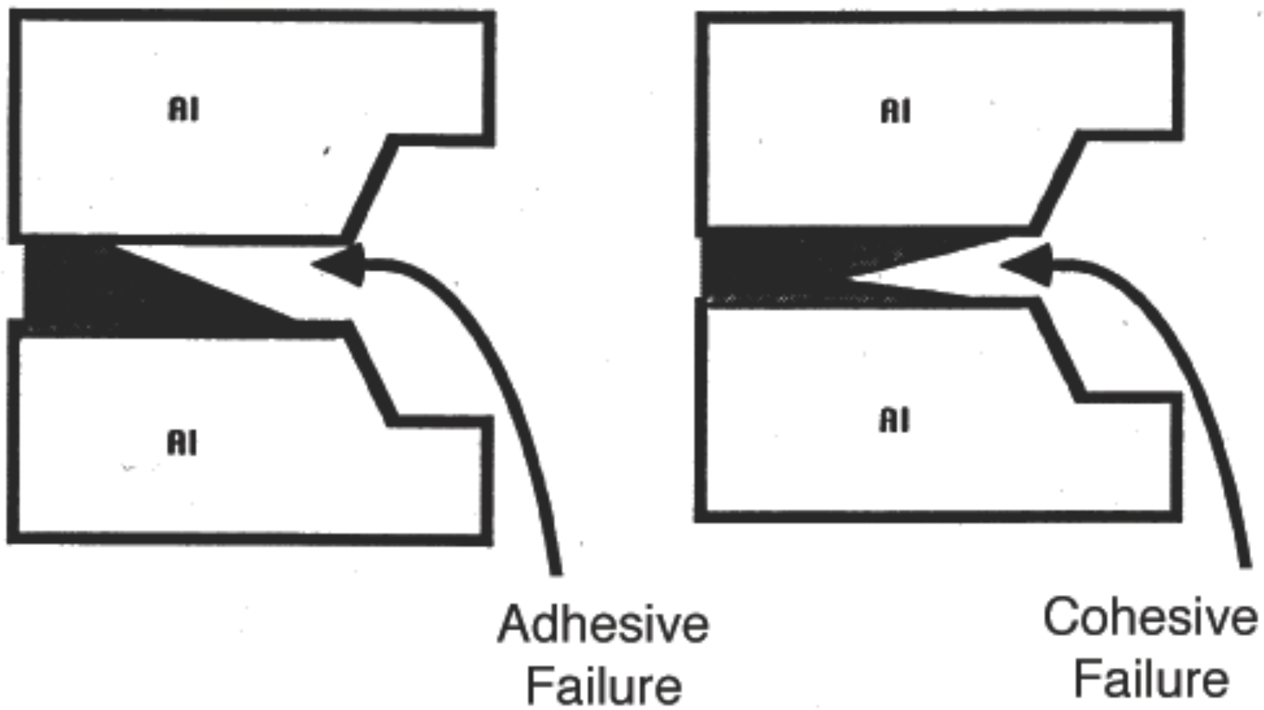
Adhesive Thickness Measurements Require Resolved Layer Reflections



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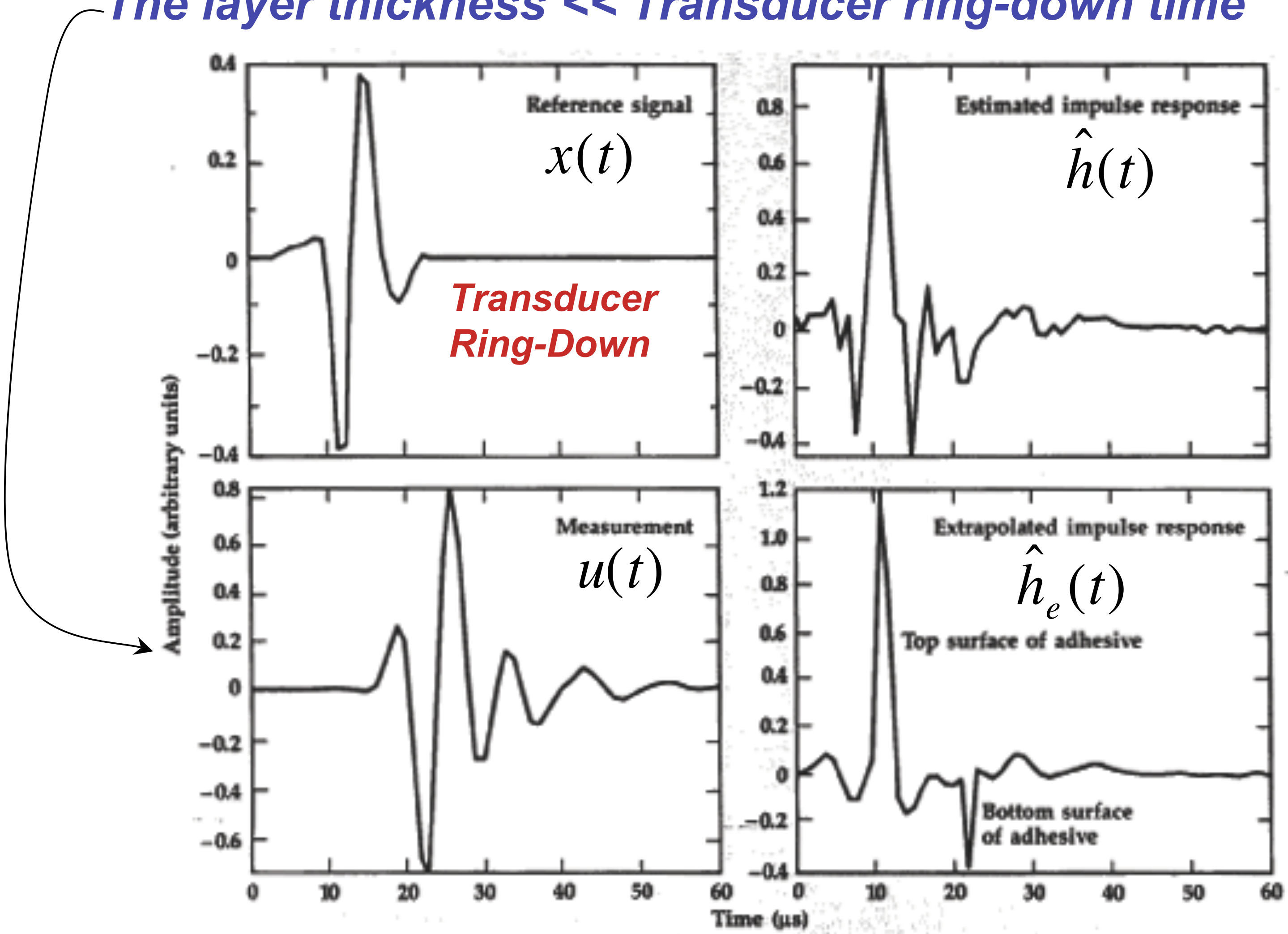
Adhesive Thickness Measurements from *Superimposed Layer Reflections*

The layer thickness << Transducer ring-down time



Conclusions

- We used MATLAB, including a GUI

- The key to dealing with the ill-posed problem is to use:
  - Prior knowledge, when available
  - Proper regularization schemes

- The regularized algorithms provide useful solutions for both simulated and real data sets

- Future work: New programmatic applications

Contingency VG's

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This work was performed under the auspices of the U.S. Department of Energy by
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Our Objective is to Improve Temporal Resolution by *Extrapolating Spectra*

- The transducer bandlimits our signals
  - System identification solutions are not unique
  - System identification solutions are valid only in a finite frequency interval *$[f_1, f_2]$.* They give us the optimal least squares solution, given the bandwidth of the transducer.
  - We can never obtain narrow impulses in the time domain

- We wish to extrapolate spectra beyond *$[f_1, f_2]$.*
  - This can allow us to obtain better approximations to impulses in the time domain.

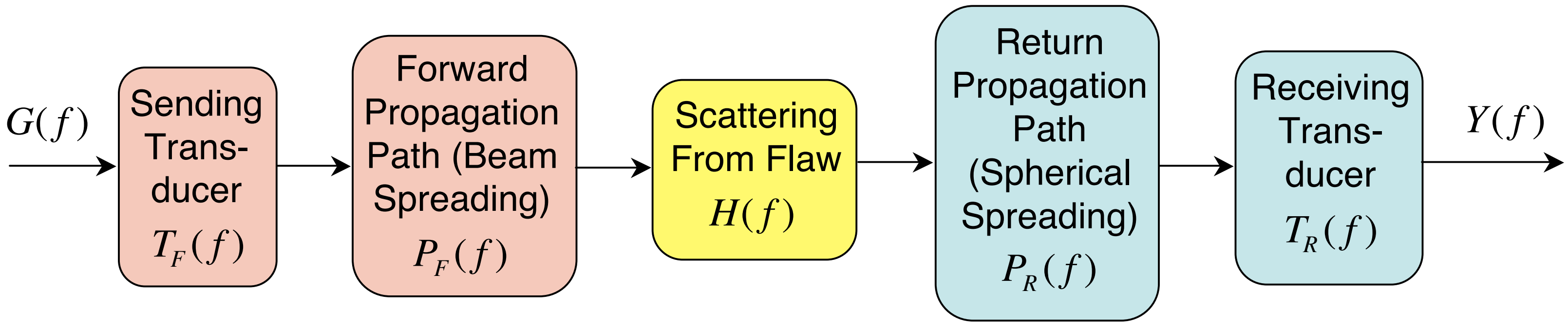
- We propose to extrapolate the spectra of:

$u(t)$ *The measured pulse-echo signal*

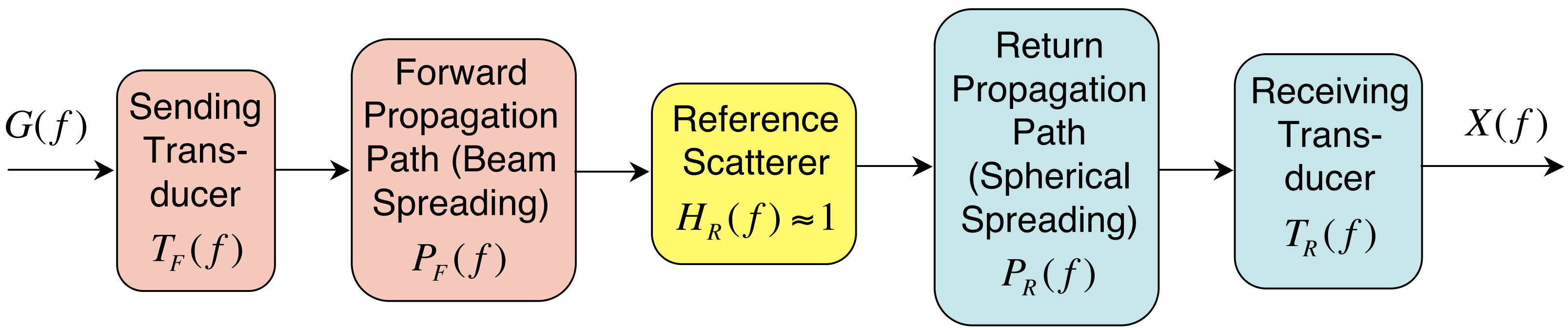
$\hat{h}(t)$ *The estimated impulse response*

We Use a Reference Scatterer to Help Remove Distortion: Conceptually, This is a *“System Identification”* Problem

Experiment to Measure the Scattered Signal $Y(f)$



Experiment to Measure the Reference Signal $X(f)$



Conceptually:

$$\frac{Y(f)}{X(f)} = \frac{\cancel{T_F(f)}\cancel{P_F(f)}H(f)\cancel{P_R(f)}\cancel{T_R(f)}}{\cancel{T_F(f)}\cancel{P_F(f)}\;(1)\;\cancel{P_R(f)}\cancel{T_R(f)}} \approx H(f) \xleftrightarrow{F^{-1}} h(t)$$